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Seismic chimney formation induced by upward-migrating methane in the Nordland Group, Southern Viking Graben

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Abstract

The Nordland Group in the Southern Viking Graben hosts seismic chimneys, represented by anomalies in seismic data and residual methane accumulations. These anomalies are generally interpreted as focused fluid flow structures, and thus pose the risk of potential fluid leakage by geological subsurface utilization. Our aim was to assess if excess pore pressure, resulting from buoyancy effects due to upward-migrating methane in the Utsira Formation may be responsible for formation of these anomalies. Our hydromechanical simulation results demonstrate that tensile failure in the Nordland Group already occurs before the maximum methane column heights develop in the Utsira Formation below.

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Keywords: Viking Graben; Nordland Group; seismic chimneys; fluid leakage; hydromechanical simulation

1. Introduction

The Southern Viking Graben hosts some of the main North Sea hydrocarbon deposits in addition to an industrial-scale CO_2 storage operation in the Neogene Utsira Formation [1–3]. In this context, caprock integrity is essential not only for mitigation of potential geogenic greenhouse gas emissions from the Jurassic hydrocarbon source rocks, but also to ensure the fulfilment of the "no leakage" criterion, defined for CO_2 storage operations by the EU CCS directive, Article 18. Regarding the Nordland Group in the Southern Viking Graben, upward migration of hydrocarbons into shallower stratigraphic units has been documented by identification of different seismically detectable features such as vertical fluid conduits, pockmarks and gas accumulations [4–6]. Specifically seismic chimneys, derived from seismic anomalies may exhibit hydraulic connections between deep and shallow aquifers in the Nordland Group, whereby the main hypothesis about their formation assumes hydraulic fracturing due to an overpressure induced by the development of a hydrocarbon gas column below the low-permeable Nordland Shale barrier [4–7].

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Different kinds of these vertical conduits have been determined worldwide [8–12], whereby the term seismic chimney is widely used [4]. With regard to caprock integrity, the understanding of the mechanisms responsible for the formation of these seismic chimneys is crucial to assess their potential contribution to upward fluid flow from deep aquifers. Hereby, especially the quantification of parameters determining the hydraulic conductivity of these vertical conduits is the focus of our research. For that purpose, we investigated the most common hypothesis on seismic chimney formation, namely that assuming the development of a gas column below the Nordland Shale due to migration of hydrocarbon gases from the Jurassic source rocks [13], by coupled hydromechanical simulations.

2. Hydromechanical model implementation

We applied a two-way coupled hydromechanical simulation model by integrating the numerical simulators MUFITS (BLACKOIL module) [14,15] and FLAC^{3D} [16] as first introduced by Kempka and Tillner [17] and further discussed by Chabab and Kempka [18] and Kempka et al. [19]. Due to the lack of stress or strain relationships applicable to determine the Nordland Shale porosity, permeability and capillary entry pressure, we considered four simulation scenarios with specific permeabilities and capillary entry pressures to result from tensile failure, i.e., pore pressure exceeding the sum of minor principal stress and tensile strength. While relative permeabilities were maintained constant for the four investigated scenarios with values of 3 mD to 3000 mD (Fig. 1), capillary entry pressures were scaled as function of gas saturation according to Leverett [20], based on the porosity and permeability present in the specific model element.

The numerical model was implemented in one dimension using the Sleipner Øst exploration well 15/9-9 data [21] with the aim to investigate the dynamics of tensile failure in the caprock as a result of the overpressure generation by buoyant forces of the steadily growing gas column (Fig. 2). For simplicity, the different sand and shale units found at the well location were integrated into three geological units, determined by averaged hydrogeological and mechanical parameters (Tab. 1), comprising the Nordland Group caprocks, the Utsira Formation and the Hordaland Group.

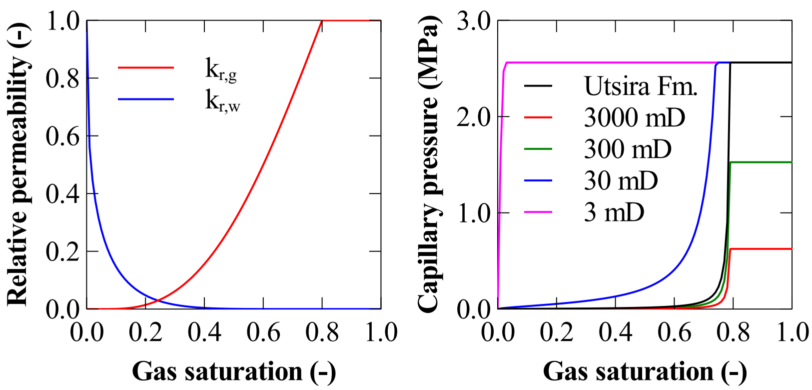

Fig. 1. Relative permeabilities (left, relative gas permeability $k_{r,g}$ and water permeability $k_{r,w}$ were chosen to be constant for all geological units). Capillary entry pressures applied for the Utsira Formation (Utsira Fm.) [22] and Nordland Group capillary entry pressures derived by Leverett-scaling based on permeabilities denoted in the figure key and porosity of 0.1025 (right).

Spatial discretization of the numerical model comprises 200 elements with a thickness of 10 m at 110 m to 2110 m depth. The Hordaland Group has a constant pore pressure in the fluid flow simulations, acting as base for the mechanical model, while Dirichlet conditions with a gas saturation equal to one were applied to the lowest element of the Utsira Formation, providing a source term for the upward migrating hydrocarbon gas. The uppermost element of the Nordland Group is also determined by a constant pressure equal to the weight of the sea water column of 110 m height.

Fluid formation volume factor, viscosity and compressibility required to parameterize the PVT tables in the MUFITS BLACKOIL model were calculated using the methane equation of state developed by Setzmann and Wagner [23] and the IWAPS formulation [24] for a temperature of 33.5 °C, representing the lower Nordland Shale

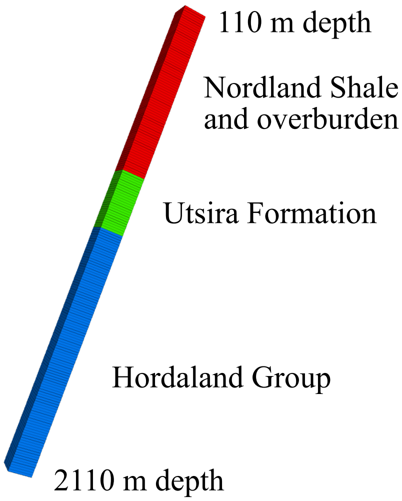

Fig. 2. Numerical 1D model geometry with 200 elements and three different geological units to assess hydromechanical effects of methane column development in the Utsira Formation in the Southern Viking Graben. Geological unit depths are indicated in Fig. 3.

and using a geothermal gradient of 0.0356 K/m and seabed temperature of 7 °C [25]. Dissolution of the hydrocarbon gas in formation water, temperature-related PVT changes and salinity were neglected due to their limited implication on the simulation results from a conservative point of view.

Table 1. Hydrogeological and mechanical parameters of three geological units incorporated into the coupled hydromechanical model to assess the hypothesis about seismic chimney formation in the Nordland Group [22,26–32].

Parameter	Unit	Nordland Group	Utsira Formation	Hordaland Group
Porosity	-	0.1025	0.42	-
Initial permeability	mD	0.001	3000	-
Density	kg/m^3	1705	1711	1705
Young's modulus	GPa	1	2	5
Poisson's ratio	-	0.17	0.18	0.20
Tensile strength	MPa	0	0	0
Friction angle	°	45	37	31
Cohesion	MPa	4	5	5
Biot's coefficient	-	1	1	1
Residual liquid saturation	-	0.2	0.2	-
Residual gas saturation	-	0.05	0.05	-
van Genuchten P_0 parameter	Pa	3580	3580	-
van Genuchten m parameter	-	0.4	0.4	-
Initial capillary entry pressure	MPa	2.5	f(gas saturation)	-
Porous media compressibility	1/Pa	7.187×10^{-10}	6.843×10^{-10}	-

A normal faulting regime with a horizontal-to-vertical-stress ratio of 0.627 was chosen according to Zweigel and Heill [32]; however, it has to be pointed out that a high uncertainty in these data exist, since the closest reliable well with stress data is more than 250 km away from the study area [34]. Fixed velocities of zero are set perpendicular to the lateral model boundaries, while the velocity at the model bottom is additionally fixed to zero in z-direction. A constant stress equal to the weight of the overlying sea water column is applied to the uppermost model element. The single hydrogeological and hydromechanical models were first equilibrated to hydrostatic and mechanical equilibrium, respectively, and then executed in a coupled scheme.

3. Simulation results

Simulation results plotted in Fig. 3 show the development of gas saturation, pore pressure as well as minor and major principal stresses for the four investigated scenarios, determined by the permeability and capillary pressure changes occurring with tensile failure in the Nordland Group. The simulations were run until a mechanical disequilibrium was achieved, i.e., the pore pressure in the upper model elements exceeded the vertical stress. This state was generally achieved within a simulation time of less than two years, assuming an infinite migration of gas into the Utsira Formation from the hydrocarbon source rocks.

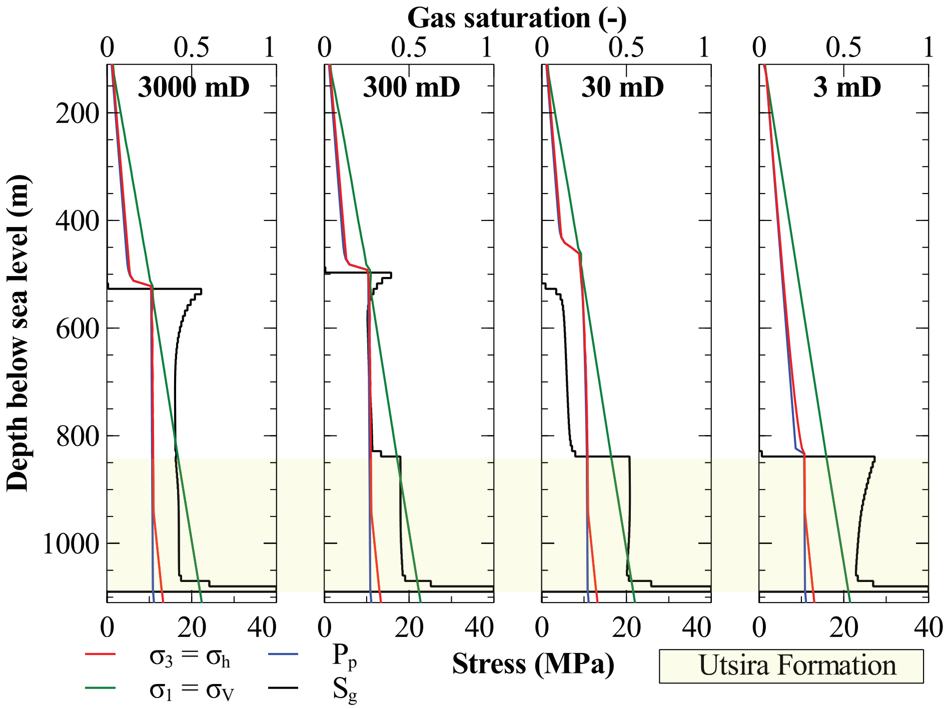

Fig. 3. Calculated stresses (major principal stress σ_1 and minor principal stress σ_3), pore pressure P_p and gas saturation S_g for the four investigated permeability-based simulation scenarios. Light yellow box marks depth of Utsira Formation.

First, it has to be noted that tensile failure in the Nordland Group and Utsira Formation is occurring in any of the four investigated scenarios at depths where pore pressure and minor principal stress become equal. Consequently, potential fluid migration paths develop due to overpressure induced by the presence of the gas column and upward pressure propagation. While the gas saturation in the Utsira Formation is almost identical in all four scenarios, expect for the case 3 mD, where gas is accumulating below the Nordland Group, we recognize significant differences in the gas saturations present in the Nordland Group between the other three scenarios, whereby saturations decrease with lower permeabilities and the related higher capillary pressures. Hence, capillary entry pressure is the key parameter for gas migration via seismic chimneys into and through the Nordland Group, while permeability only determines at which time-scale gas migration occurs.

We would like to emphasize that upward gas migration in the 3000 mD, 300 mD and 30 mD cases is determined by the choice of hydromechanical boundary conditions, considering the limitation that pore pressure is not allowed to exceed the vertical stress in order to maintain mechanical equilibrium at the end of a coupling step. Consequently, one can assume that a full development of the seismic chimneys up to the top of the Nordland Group occurs in any of these three scenarios. However, significant differences in gas saturations develop in the Nordland Group in these three scenarios, depending on the capillary pressure, scaled using the initial porosity and updated permeability.

4. Discussion and conclusions

We investigated one common hypothesis on the formation of seismic chimneys in the Southern Viking Graben, North Sea, by coupled hydromechanical simulations. This hypothesis considers the formation of a gas column in the Utsira Formation due to gas migration from the Jurassic hydrocarbon source rocks to result in a formation overpressure, inducing tensile failure, and thus hydraulic conductivity in the overburden. Due to the general lack of experimental data on relationships between strain or stress to porosity, permeability and capillary entry pressure of the Utsira Formation and the entire Nordland Group, we considered four scenarios with different permeability changes occurring when tensile failure in the Nordland Group is experienced.

Our simulation results demonstrate that for permeability increases to a few tens of milliDarcies and above, seismic chimneys develop by tensile failure in the Nordland Group, assuming a continuous gas supply from the hydrocarbon source rocks. However, tensile failure is also occurring when lower permeabilities are assigned to the Nordland Group, whereby gas migration is hindered by relatively high capillary entry pressures, scaled to the updated porosity and permeability of the respective mechanically failed elements in the Nordland Group. These differences in capillary entry pressures are also responsible for different evolving gas saturations in the overburden, which may be used as an indicator for hydraulic properties by means of seismic monitoring methods. At this point, we want to emphasize that the seismic chimney development in our models is limited by the chosen hydromechanical boundary conditions at the model top, which may be addressed by the choice of different hydraulic boundary conditions in future modelling activities. However, we expect that the seismic chimneys develop up to the top of the Nordland Group for permeability changes resulting in tens of milliDarcies.

We tested different stress/strain-to-porosity/permeability relationships found in the literature [35–38] with our model, resulting in a lack of enhanced porosities and permeabilities in the presence of tensile failure, even for maximum values of specific fitting parameters. The general lack in experimental data emphasizes that extensive scientific research is required in sample acquisition by offshore drilling campaigns, in situ and ex situ testing as well as combined monitoring to improve the understanding of seismic chimney implications on hydrocarbon gas leakage quantification in the North Sea by deriving realistic relationships between stress or strain and porosity, permeability and especially the capillary entry pressure as a key parameter for gas migration.

In addition to a revision of the upper hydromechanical boundary condition in the model, we aim to extend the 1D model to the second dimension, considering the spatial heterogeneity of the Nordland Group geological units in porosity and permeability, using a full-scale geological model available for the study area in the Southern Viking Graben [39]. This will allow us to validate the modelling results in terms of matching the diameter of the seismic chimneys generated by coupled hydromechanical modelling against available geophysical data.

References

[1] Justwan H, Dahl B. Quantitative hydrocarbon potential mapping and organofacies study in the Greater Balder Area, Norwegian North Sea. In: Dore AG, Vining BA, editors. Petroleum Geology of North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference. Geol. Soc. London; 2005. p. 1317–1329.

[2] Eiken O, Ringrose P, Hermanrud C, Nazarian B, Torp TA, Hoier L. Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit. Energy Procedia 2011;4:5541–5548.

[3] Arts R, Chadwick RA, Eiken O, Thibeau S, Nooner S. Ten years' experience of monitoring CO_2 injection in the Utsira sand at Sleipner, offshore Norway. First Break 2008;26:65–72.

[4] Karstens J, Berndt C. Seismic chimneys in the Southern Viking Graben Implications for palaeo fluid migration and overpressure evolution. Earth Planet Sc. Lett. 2015;412:88–100.

[5] Cartwright J, Huuse M, Aplin A. Seal bypass systems. Am. Assoc. Pet. Geol. 2007;91:1141–1166.

[6] Løseth H, Gading M, Wensaas L. Hydrocarbon leakage interpreted on seismic data. Mar. Pet. Geol. 2009;26:1304–1319.

[7] Berndt C. Focused fluid flow in passive continental margins. Philos. Trans. R. Soc. A, Math. Phys. Eng. Sci. 2005;363:2855–2871.

[8] Løseth H, Wensaas L, Arntsen B, Hanken NM, Basire C, Graue K. 1000 m long gas blow-out pipes. Mar. Pet. Geol. 2011;28:1047–1060.

[9] Bünz S, Mienert J, Berndt C. Geological controls on the Storegga gashydrate system of the mid-Norwegian continental margin. Earth Planet. Sci. Lett. 2003;209:291–307.

[10] Hovland M, Sommerville JH. Characteristics of two natural gas seepages in the North Sea. Mar. Pet. Geol. 1985;2:319–326.

[11] Granli JR, Arntsen B, Sollid A, Hilde E. Imaging through gas-filled sediments using marine shear-wave data. Geophysics 1999;64:668–677.

[12] Arntsen B, Wensaas L, Løseth H, Hermanrud C. Seismic modeling of gas chimneys. Geophysics 2007;72:251–259.

[13] Cathles LM, Su Z, Chen D. The physics of gas chimney and pockmark formation, with implications for assessment of seafloor hazards and gas sequestration. Mar. Pet. Geol. 2010;27:82–91.

[14] Afanasyev AA. Hydrodynamic Modelling of Petroleum Reservoirs using Simulator MUFITS. Energy Procedia 2015;76:427–435.
[15] Afanasyev AA, Kempka T, Kühn M, Melnik O. Validation of the MUFITS reservoir simulator against standard industrial simulation tools for CO_2 storage at the Ketzin pilot site. Energy Procedia 2016;this issue.
[16] Itasca. FLAC^{3D} Software Version 5.01. Users Manual. Advanced Three-Dimensional Continuum Modelling for Geotechnical Analysis of Rock, Soil and Structural Support. 2013.
[17] Kempka T, Tillner E. Caprock Permeabilities Must be Considered in Assessments of Ground Surface Displacements in Geological Underground Utilization. Energy Procedia 2015;76:59–599.
[18] Chabab E, Kempka T. Quantification of fluid migration via faults requires two-way coupled hydromechanical simulations. Energy Procedia 2016;this issue.
[19] Kempka T, Nakaten B, Chabab E, De Lucia M, Nakaten N, Otto C, Pohl M, Kühn M. Flexible simulation framework to couple processes in complex 3D models for subsurface utilization assessment. Energy Procedia 2016;this issue.
[20] Leverett MC. Capillary behaviour in porous solids. Transactions of the AIME 1941:142:159–172.
[21] Norwegian Petroleum Directorate 2015. http://factpages.npd.no (last accessed: 27 May 2016).
[22] Khattri SK, Fladmark GE, Hellevang H, Kvamme B. Simulation of Long-Term Fate of CO_2 in the Sand of Utsira. J. Porous Media 2011; 14(2):149–166.
[23] Setzmann U, Wagner W. A New Equation of State and Tables of Thermodynamic Properties for Methane Covering the Range from the Melting Line to 625 K at Pressures up to 1000 MPa. J. Phys. Chem. Ref. Data 1991;20(6):1061–1151.
[24] Wagner W, Pruss A. The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use. J. Phys. Chem. Ref. Data 2002; 31(2):387–535.
[25] Singh VP, Cavanagh A, Hansen H, Nazarian B, Iding M, Ringrose PS. Reservoir Modeling of CO_2 Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway. SPE Annual Technical Conference & Exhibition, Florence, Italy, 19–22 September. 2010.
[26] Harrington JF, Noy DJ, Horseman ST, Birchall DJ, Chadwick RA. Laboratory study of gas and water flow in the Nordland Shale, Sleipner, North Sea. In: Grobe M, Pashin JC, Dodge RL, editors. Carbon dioxide sequestration in geological media - State of the Science; 2009, 521–543.
[27] Johnston DH, editor. Investigations in Geophysics Methods and Applications in Reservoir Geophysics, Society of Exploration Geophysicists; 2010. 669 pp.
[28] Audigane P, Gaus I, Pruess K, Xu T. A Long-Term 2D Vertical Modeling of the CO_2 Storage at Sleipner (North Sea) Using TOUGHREACT. Proceedings of TOUGH Symposium 2006, Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006.
[29] Hettema MHH, Jranson H. Characterization of two shallow aquifers for produced water injection. In American Rock Mechanics Association, 46th US Rock Mechanics / Geomechanics Symposium. Chicago; 2012.
[30] Chadwick RA, Noy DJ, Holloway S. Flow processes and pressure evolution in aquifers during the injection of supercritical CO_2 as a greenhouse gas mitigation measure. Petrol. Geosci. 2009;15(1):59–73.
[31] Kemp SJ, Pearce JM, Steadman EJ. Mineralogical, geochemical and petrographical characterisation of Nordland Shale cores from well 15/9–A–11, Sleipner field, northern North Sea. Sustainable Energy and Geophysical Surveys Programme. Commissioned Report CR/02/313, British Geological Survey, Keyworth, Nottingham; 2002.
[32] Zweigel P, Heill LK. Studies on the likelihood for caprock fracturing in the Sleipner CO_2 injection case A contribution to the Saline Aquifer CO_2 Storage (SACS) project. 2003. Unpublished SACS project report SINTEF Petroleum Research. Unpublished report; 2003.
[33] Zweigel P, Arts R, Lothe AE, Lindeberg EBG. Reservoir geology of the Utsira Formation at the first industrial-scale underground CO_2 storage site (Sleipner area, North Sea). Geological Society, London, Special Publications 2004, 233(1):165–180.
[34] Heidbach O, Tingay M, Barth A, Reinecker J, Kurfe D, Müller B. The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.
[35] Rutqvist J, Wu YS, Tsang CF, Bodvarsson G. A modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock. Int. J. Rock Mech. Min. 2002;39(4):429–442.
[36] Olivella S, Alonso EE. Gas flow through clay barriers. Géotechnique 2008;58(3):57–176.
[37] Olivella S, Gens A. Double structure THM analyses of a heating test in a fractured tuff incorporating intrinsic permeability variations. Int. J. Rock Mech. Min. 2005;42(5–6):667–679.
[38] Chin LY, Raghavan R, Thomas LK. Fully-coupled geomechanics and fluid-flow analysis of wells with stress-dependent permeability. SPE Journal 2000;5(1):32–45.
[39] Bünz S, Tasianas A, Karstens J, Berndt C, Darcis M, Flemisch B. Sub-seabed CO_2 Storage: Impact on marine ecosystems (ECO_2), Milestone Report (MS12): geological models for industrial storage sites, University of Troms, Norway, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany and University of Stuttgart, Germany; 2012.